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Seasonal variation in grain yield and quality in different rice varieties

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ABSTRACT

Rice grain quality and yield, which are adversely affected by suboptimum condition in the climatic environment, are expected to be affected more severely under climate change. Adaptation to climate variation therefore requires stability in grain quality as well as yield. Grain yield and quality of four modern rice varieties were shown to respond differently to the climatic condition of the wet, cool and hot season at Chiang Mai, Thailand. The variation in grain yield was associated with differential effects of season on grain filling in different varieties. A simple dilution effect on nutritional quality was indicated by inverse relation between grain yield and the concentration of nitrogen, phosphorus, iron and zinc in the endosperm, i.e. the white rice normally consumed by rice eaters. The rice varieties also showed differential response to season in their head rice yield, grain chalkiness and gelatinization temperature, independently of the grain yield. The relationship between head rice yield and grain chalkiness was not significant, although some complex physico-chemistry of the starch was suggested by the correlation between grain chalkiness and gelatinization temperature. The effects of variety and season found here suggested that evaluation of rice genotypes for adaptation to climate change will need to consider grain quality along with grain yield.

1. Introduction

In monsoonal Asia rice is generally grown in the wet season and in the dry season in irrigated area, which covers more than half of the rice land in the continent (GRiSP, 2013). The rice crop in each location is therefore subjected to different sets of environmental condition in the different cropping seasons, the difference that can be expected to be amplified with climate change. Seasonal effects on rice yield in the tropics are well established. For example, wet season yield is likely to be lower than dry season yield when the solar radiation reaching the canopy is limited by the clouds (Yoshida, 1981). Extreme temperature during the hot dry summer is also detrimental to grain yield through adverse effects on pollination and fertilization (Matsui et al., 2000, 2001; Nakagawa et al., 2002), with significant variation in the sensitivity among rice varieties (Satake and Yoshida, 1978; Jongjaidee et al., 2010).

Rice grain quality is determined by genetic control and environmental conditions during the growing season. Global warming and climate change pose a threat to rice yield, but the adverse effects on grain quality would also depress economic value of the harvest. Temperature is one of the factors affecting rice yield and quality. It has been reported that within a certain range nighttime temperature has more pronounced negative effects on rice than daytime temperature (Peng et al., 2004). High nighttime temperature during kernel development caused spikelet infertility (Jagadish et al., 2007; Matsui et al., 1997; Mohammed and Tarpley, 2009, 2010), lower grain weight and yield (Peng et al., 2004), greater proportion of chalky grain (Cooper et al., 2008; Ishimaru et al., 2009; Tashiro and Wardlaw, 1991; Tsukaguchi and Iida, 2008), lower head rice yield (Ambardekar et al., 2011; Cooper et al., 2008; Counce et al., 2005), and also affected grain physicochemical attributes by lowering amylose content (Cooper et al., 2008). Low temperature extended grain maturity period and ultimately resulting in higher thousand grain weight (Funaba et al., 2006).

However, the available information on the environment and grain quality has focused mostly on japonica rice of the temperate region and much less on indica rice, the main type of rice in the tropics. Furthermore, grain quality in rice is defined by many different characteristics (Juliano, 1993). Some of these are translated directly to price, e.g. head rice yield, aroma, and the physical appearance of the milled rice such as grain translucency and vitreousness (e.g. Leesawatwong et al., 2003), with some characteristics such as grain chalkiness being more critical in certain markets (Sriswasdilek et al.,

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1992; Efferson, 1985). The grain nutrient content, on the other hand, has important nutritional implications for rice eaters (IFPRI, 1999). Therefore, this present study set out to explore how the different quality characteristics of 4 indica varieties of Thai rice are affected along with yield when grown in different cropping seasons.

2. Materials and methods

2.1. Rice varieties and culture

A field experiment was conducted at Chiang Mai University, Thailand (18°47′N, 98°57′E) with three of Thailand's mega-varieties, Suphan Buri 1 (SPR1), Chai Nat 1 (CNT1) and Pathum Thani 1 (PTT1), plus RD21, a modern variety adapted to the highlands, grown in a randomized complete block design with four independent replications. The varieties were of long (> 6.61–7.50 mm of grain length) and slender grain shape (length/width ratio > 3.0) (Jennings et al., 1979). The experiment was repeated over 3 seasons: wet season (13 Aug–23 Nov 2009), cool season (13 Oct 2009–10 Feb 2010) and hot season (5 Feb–16 Jun 2010). One month old seedlings were transplanted into 4 × 4 m plots, one plant per hill at 0.25 × 0.25 m spacing.

Fertilizers applied to all plots was 28 kg N ha^{-1}, 28 kg P_2O_5 ha^{-1} and 28 kg K_2O ha^{-1} at 15 days after transplanting, followed by 43 kg N ha^{-1} urea top dressing at panicle initiation. Hand weeding was done at 3 weeks after transplanting and before panicle emergence. The experimental field was flooded to 10–15 cm depth and maintained until 7 days before harvest. Weather data (daily maximum/minimum temperature; rainfall, relative humidity and sunshine hours) for the whole growing seasons were obtained from the Northern Meteorological Centre, Chiang Mai, Thailand located 2.5 km from the experimental site, and having similar micro-climate as the experimental site.

2.2. Sample preparation and head rice yield

Two 1 × 1 m quadrats were harvested manually from each plot at physiological maturity to measure grain weight and grain size distribution was determined from the weight of individual un-husked (paddy rice) grain, including filled, partially filled and unfilled. Single grain weight was determined by weighing and recording the weight each grain individually from a randomly subsample of 300 grains from each replication (Leesawatwong, 2005). Grain size distribution was represented as percentage of grains belonging to each class of grain size. The grain samples were air dried to 11–12% of moisture content for grain quality evaluation. One-hundred g of the paddy rice was dehusked with a laboratory husker machine (model P-1, Ngek Seng Huat, Thailand) to produce brown rice (whole caryopsis with intact pericarp and embryo). The husker was Teflon-coated in all parts and handles to avoid Fe contamination during the de-husking process (Prom-u-thai et al., 2007a,b). Thirty g of whole grain brown rice were polished for 30 s with a laboratory milling machine (model K-1, Ngek Seng Huat, Thailand) to yield white rice, then manually separated into head rice (≥4/5 whole grain length, Ministry of Commerce, 2016) and remainder as broken rice. All grain samples were weighed for determination of head rice yield, defined as the weight of head rice as percentage of paddy weight.

2.3. Grain chalkiness and alkaline spreading value

Grain chalkiness was evaluated based on the Standard Evaluation System (SES Scale) (IRRI, 1979). Ten g of head rice were visually inspected for presence of chalky areas and manually separated into two categories, namely grain with chalky area ≥20% of rice grain area as chalky grain, and grain with chalky area < 20% of grain area as non-chalky grain. Percent grain chalkiness was calculated by chalky grain weight per head rice weight. Gelatinization temperature was assessed with alkali spreading assay (IRRI, 1979). One hundred whole grains of milled rice from each experimental unit were placed individually in Petri dishes (20 grains per dish, each containing 10 ml of 1.7% KOH, total of 5 Petri dishes per treatment), then kept at room temperature for 23 h. Four milled grains of KDML105 (low gelatinization temperature) and RD4 (high gelatinization temperature) grown in the wet season, 2009 at Chiang Mai University were used as checks. The degree of spreading was assessed at the 24th h, using a seven-point scale of 1–7, the lower score indicating higher gelatinization temperature.

2.4. Nitrogen, phosphorus, zinc and iron analysis

Ten g samples of brown and white rice were oven dried at 75 °C for 72 h then 1 g was dry-ashed in a muffle furnace at 535 °C for 8 h. The ash was dissolved in HCl (1:1; HCl to deionized water), the concentration of P was determined colorimetrically (Murphy and Riley, 1962), and Fe and Zn with a Hitachi Z-8230 atomic absorption spectrophotometer (AAS) (Zarcinas et al., 1987). Nitrogen was analyzed by the Kjeldahl method (Jackson, 1967). Soybean leaf powder was used for reference material in all samples to check the quality of the analyses.

2.5. Statistical analysis

Analysis of variance was conducted to detect differences in grain yield, and grain quality characteristics using Statistic 8 (analytical software, SXW). Data were analyzed in factorial in randomized complete block design. Data in percentage were arcsine transformed (as proportion of filled grain, head rice yield and chalk grain) to normalize the variance before analysis. The least significant difference (LSD) at $p < 0.05$ was applied to compare the means for significant differences between variety and cropping season.

3. Results

3.1. Climatic data during the growing season

The rice varieties in the experiment took 102 days from transplanting to harvest in the wet season, 119–126 days in the cool season and 111–131 days in hot season, with some variation in the climatic condition between the seasons (Fig. 1). The wet season received most of the rain at 522 mm, followed by the hot season with 236 mm in the hot season, almost all of which rain fell in the first 3 weeks, and the cool season had only 113 mm of rain. Relative humidity averaged 73.6% in the wet season, 68.1% in the cool season and 59.4% in the hot season. The temperature from transplant to panicle emergence averaged 28.7 ± 1.0 °C in the wet season, 26.2 ± 2.5 °C in the cool season, 28.7 ± 2.9 °C in the hot season; and from panicle emergence to harvest 27.3 ± 1.6 °C in the wet season, 24.2 ± 1.3 °C in the cool season, 31.6 ± 1.4 °C in the hot season. Although some of the average temperatures for the seasons were within the same or close range, there were clear differences between seasons in the patterns of daily minimum and maximum temperatures as well as in the temperatures during anthesis. The average daily sunshine was 6.9 h in wet season, 8.5 h in the cool season and 8.7 h in the hot season.

3.2. Grain yield and yield components

The grain yield of all four rice varieties, highest in the wet season and lowest in the cool season, were correlated positively with% of filled grain but negatively with the number of tillers and panicles (Table 1). The number of tillers and panicles per plant were affected by the interaction between variety and season with the highest number of tillers and panicles in the cool season compared with the wet and hot seasons in all varieties but in different ratio between seasons among varieties. The number of spikelets per hill was unaffected by season, although it differed among the varieties, with SPR1 and CNT1 producing the largest number of spikelets, followed by PTT1 and then RD21. Percentage

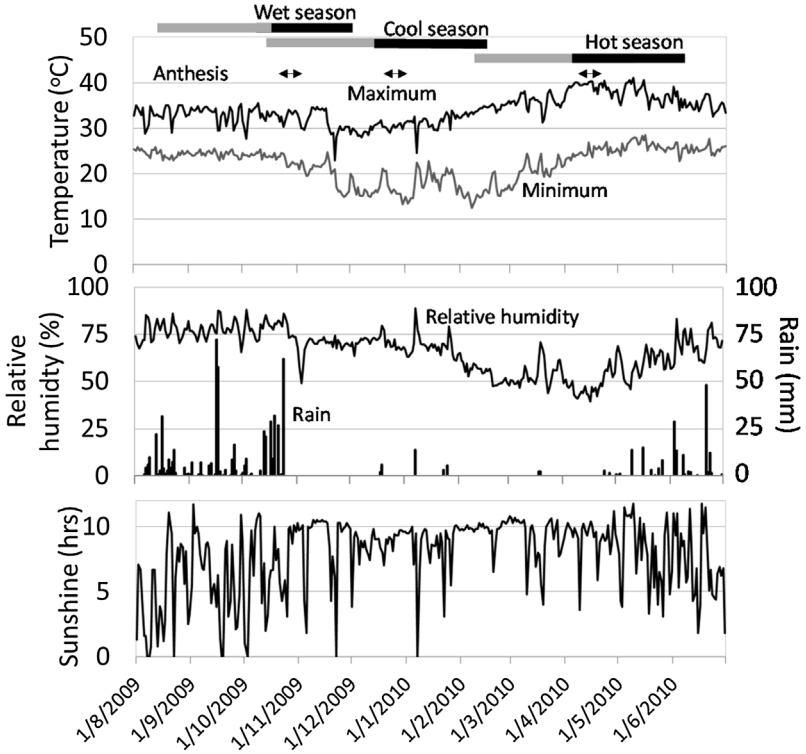

Fig. 1. Temperature, humidity, rainfall, hours of sunshine, duration of three rice cropping seasons (transplanting to panicle emergence ▬; panicle emergence to harvest ▬), and approximate time of anthesis.

of filled grain, which strongly correlated with yield ($r = 0.91$, $p < 0.001$), exhibited clear seasonal effects that differed significantly among the varieties. The wet season planting produced the most complete grain filling at close to 90% in all four rice varieties. In the cool season only about half of the grain in SPR1 and RD21 was filled, while in CNT1 and PTT1 it was less than 30%. The percentage of filled grain correlated negatively with number of tillers and panicles, but positively with average temperature from transplanting to panicle initiation (Table 1).

The pattern of individual grain weight distribution of each rice variety was different among cropping seasons (Fig. 2). For each variety the frequency of the modal grain weight varied with the season, but the modal grain weight remained constant across the three seasons. The rice varieties all had higher proportion of the modal grain weight in the wet and hot season seasons than in the cool season when there were more unfilled or partially filled grain, but with different extent of the cool season decline among the varieties. For SPR1, CNT1 and PTT1, the modal grain weight of 28 mg grain^{-1} accounted for 70–80% of all the grains in the wet and hot season, but declining in the cool season to 50% in SPR1 but to less than 30% in CNT1 and PTT1. In RD21, the modal grain weight of 35 mg grain^{-1} accounted for 63% of the grain in the wet and 66% in the hot season, declining to 39% of the grain in the cool season. Thus the cool season depression of grain filling was strongest in CNT1 and PTT1, less in RD21 and weakest in SPR1.

3.3. Grain physico-chemical quality

Head rice yield, grain chalkiness and alkali spreading value of the rice varieties were affected differently among the rice varieties, but none of these quality characteristics showed significant association with the grain yield (Table 2). The head rice yield was generally highest in the wet season. The varieties SPR1 and CNT1 showed small depression in head rice yield in the cool and hot season. The same high head rice yield was maintained across all three seasons in RD21, while PTT1 produced similar level of head rice yield in the wet and cool seasons, and a significant decline in the hot season.

Season affected grain chalkiness differently among the rice varieties, although the hot season produced the highest percentage of chalky grain in all four varieties. SPR1 which had the highest chalky grain at 75% in the hot season crop produced grain with only 27% in the wet season and almost no chalkiness in the cool season. The same seasonal pattern was seen in PTT1 although it generally had less than half the chalkiness of SPR1. In the wet and cool season CNT1 had the lowest percentage of chalky grain, in the same range as PTT1, but in the hot season its grain chalkiness was significantly higher than PTT1 although not as high as SPR1. RD21 was consistently high in grain chalkiness, which was as high to almost as high as the most chalky variety for the season. There was also significant interaction between the effect of variety and season on the alkali spreading value, which ranged from 2.1 to 7.0. When grown in the wet season RD21 had the same alkali spreading value of 7, similar to the low gelatinization temperature check KDML105, PTT1 was significantly lower at 5.2, while the value for SPR1 and CNT1 were approaching the high gelatinization temperature check RD4. Varietal differences were observed in the seasonal effects on alkali spreading values. In the varieties CNT1, PTT1 and RD21 the hot season alkali spreading value was lower than in the wet and cool season which were not different, but in the variety SPR1 the alkali spreading value was lowest in the hot and highest in the cool season, with the value in the wet season falling between the two extremes. Head rice yield significantly correlated with alkali spreading value ($r = 0.60$, $p < 0.05$), but not with grain chalkiness, neither was there any association between grain chalkiness and alkali spreading value.

3.4. Nutrient contents

The interaction between the effect of variety and season on the concentration of the macronutrients N and P was significant in both brown and white rice (Table 3). The interaction between the effect of variety and season was significant on the Zn concentration in brown and white rice, and the Fe in brown rice but not on the Fe in white rice (Table 4). The brown and white rice N concentration were closely correlated ($r = 0.99$ $p < 0.001$), and so were those of P ($r = 0.80$ $p < 0.001$) and Zn ($r = 0.97$ $p < 0.001$), but not Fe ($r = 0.40$ NS at

Table 1
Grain yield and yield components of four rice varieties grown in three seasons in Chiang Mai, Thailand.

Variety	Season	Grain yield (t ha^{-1})	Tillers plant^{-1}	Panicles plant^{-1}	Spikelets panicle^{-1}	Filled grain (%)
SPR1	Wet	5.51	11.8abc	11.3bc	1245	87.4e
	Cool	4.16	21.1e	16.6f	1281	50.9b
	Hot	4.99	14.2bcd	13.0cde	1408	69.6cd
CNT1	Wet	5.47	15.3cd	14.5ef	1214	87.9e
	Cool	2.60	47.5g	38.4h	1324	29.3a
	Hot	4.68	15.0cd	13.0cde	1257	72.1cde
PTT1	Wet	5.01	14.7bcd	13.5cde	1169	85.6de
	Cool	2.56	28.8f	19.9g	1216	26.9a
	Hot	4.03	15.1cd	13.8de	1079	74.5de
RD21	Wet	5.06	8.9a	8.1a	976	88.3e
	Cool	3.28	17.1de	11.7bcd	994	55.4bc
	Hot	4.30	10.7ab	9.8ab	953	83.3de
Variety mean						
SPR1		4.89a	15.7	13.6	1311a	69.3
CNT1		4.25b	25.9	21.9	1265a	63.1
PTT1		3.87b	19.5	15.7	1154b	62.3
RD21		4.21b	12.2	9.8	974c	75.6
Season mean						
	Wet	5.26a	12.6	11.8	1151	87.3
	Cool	3.15c	28.6	21.6	1203	40.6
	Hot	4.50b	13.7	12.4	1174	74.8
Significant effects by analysis of variance						
Variety	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.01$	$p < 0.001$	
Season	$p < 0.001$	$p < 0.001$	$p < 0.001$	$NS_{0.05}$	$p < 0.001$	
Variety × season	$NS_{0.05}$	$p < 0.001$	$p < 0.00$	$NS_{0.05}$	$p < 0.001$	
Correlation (r), with significance by analysis of variance						
With mean T1[1]	0.35	−0.44	−0.43	−0.15	0.91	
	$NS_{0.05}$	$NS_{0.05}$	$NS_{0.05}$	$NS_{0.05}$	($p < 0.001$)	
With mean T2[2]	0.13	−0.52	−0.54	−0.77	0.56	
	$NS_{0.05}$	$NS_{0.05}$	$NS_{0.05}$	$NS_{0.05}$	$NS_{0.05}$	
With grain yield		−0.77 $p < 0.001$	−0.66 $p < 0.05$	0.02 $NS_{0.05}$	0.91 $p < 0.001$	
With% filled grain		−0.85 $P < 0.001$	−0.75 $p < 0.01$	0.05 $NS_{0.05}$	–	

Significant difference within column (by $LSD_{0.05}$) indicated by different letters.
[1] T1 = average temperature from transplanting to panicle initiation.
[2] T2 = average temperature from panicle initiation to harvest.

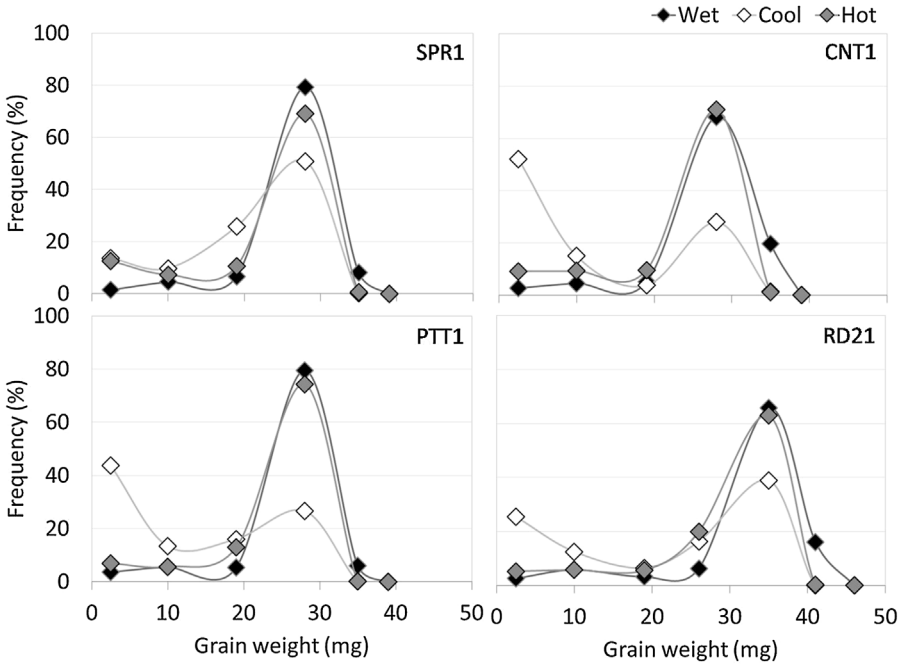

Fig. 2. Frequency of single grain weight among four rice varieties grown in wet, cool and hot seasons.

Table 2
Grain quality characteristics of four rice varieties grown in three seasons in Chiang Mai, Thailand.

Variety	Season	Head rice yield (%)	Grain chalkiness (%)	Alkali spreading value[1]
SPR1	Wet	65.4e	27.0d	2.8ab
	Cool	47.9bc	5.3ab	3.1b
	Hot	45.0ab	75.0g	2.1a
CNT1	Wet	58.4de	8.1ab	3.5c
	Cool	43.9ab	14.1bc	3.8c
	Hot	44.0ab	43.4e	2.4a
PTT1	Wet	47.4bc	12.4abc	5.2de
	Cool	54.6cd	2.4a	5.6e
	Hot	37.8a	30.0d	3.3c
RD21	Wet	70.1e	22.0cd	7.0f
	Cool	64.4e	29.5d	7.0f
	Hot	63.8e	55.4f	4.8d
Significance effects by analysis of variance				
Variety		$p < 0.001$	$p < 0.001$	$p < 0.001$
Season		$p < 0.001$	$p < 0.001$	$p < 0.001$
Variety × season		$p < 0.01$	$p < 0.001$	$p < 0.001$
Correlation (r), with significance by analysis of variance				
With grain yield		0.23 ($NS_{0.05}$)	0.27 ($NS_{0.05}$)	−0.32 ($NS_{0.05}$)
Between quality characteristics				
With head rice yield			−0.06 ($NS_{0.05}$)	0.60 ($p < 0.05$)
With chalkiness				−0.32 ($NS_{0.05}$)

Significant difference within column (by $LSD_{0.05}$) indicated by different letters.
[1] The value for KDML105 (low gelatinized temperature check) = 7; RD4 (high gelatinized temperature check) = 2.

Table 3
Nitrogen and phosphorus concentration in brown and white rice in four rice varieties grown in three seasons in Chiang Mai, Thailand.

Variety	Season	Nitrogen		Phosphorus	
		Brown rice	White rice	Brown rice	White rice
		(% dry weight)			
SPR1	Wet	1.49c	1.36b	0.35a	0.09a
	Cool	2.09d	1.92c	0.41d	0.13e
	Hot	1.23a	1.13a	0.34a	0.10b
CNT1	Wet	1.54c	1.47b	0.38bc	0.11c
	Cool	2.69f	2.62e	0.50f	0.17g
	Hot	1.28ab	1.19a	0.36ab	0.12d
PTT1	Wet	1.46bc	1.40b	0.35a	0.11c
	Cool	2.53ef	2.47d	0.48e	0.17g
	Hot	1.20a	1.15a	0.35a	0.14f
RD21	Wet	1.44bc	1.40b	0.36ab	0.10b
	Cool	2.46e	2.42d	0.40cd	0.17g
	Hot	1.44bc	1.22ab	0.38bc	0.12d
Significant effects by analysis of variance					
Variety		$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Season		$p < 0.01$	$p < 0.01$	$p < 0.001$	$p < 0.001$
Variety × season		$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$
Correlation (r), with significance by analysis of variance					
Between brown and white rice		0.99 $p < 0.001$		0.80 $p < 0.001$	
With grain yield		−0.83 $p < 0.001$	−0.83 $p < 0.001$	−0.85 $p < 0.001$	−0.96 $p < 0.001$

Significant difference within column (by $LSD_{0.05}$) indicated by different letters.

$p < 0.05$). The main differences in the seasonal effects among the varieties was in the extent to which concentration of the nutrients, including N, P, and Zn in brown rice and white rice and Fe in brown rice, were elevated in the cool season, and the differential effects of the hot season on the concentration of different nutrients. In the wet season N concentration were not significantly different among the varieties in both brown and white rice, but the N were significantly higher in the cool season, by 40% in SPR1, and 70% higher in CNT1, PTT1 and RD21. In the hot season the brown and white rice N in SPR1, CNT1 and PTT1 and white rice N in RD21 were about 80% of the wet season N, although RD21 had the same brown rice N in the hot and wet season. The brown rice P, which differed only slightly among the rice varieties and between the wet and hot season, was elevated in the cool season to different extent among the varieties, being highest in CNT1, followed by PTT1, SPR1 and RD21, in that order. The white rice P concentration, which was only a fraction of the brown rice P, was affected by the variety and season differently from the brown rice P. In all four varieties the white rice P was lowest in the wet season, higher in the hot season and highest in the cool season, but with different seasonal effects in different varieties. The white rice P concentration of the four varieties in the hot season ranged from 109% to 127% and the cool season concentration ranged from 144% to 170% of their P concentration in the wet season. The polishing of brown rice to produce white rice resulted in a lowering of the grain Zn concentration by one-fifth on average. The brown and white rice Zn were similarly affected by variety and season. With some slight differences among the varieties and between the wet and hot season, the brown rice and white rice Zn in all four varieties were significantly higher in the cool season, when brown rice Zn of the varieties ranged from 26% to 38% higher, and white rice Zn from 33% to 79% higher, than their wet season concentration. There was no significant interaction effect of variety and season on the Fe in white rice, which had declined to only 2–4 mg Fe kg^{-1} after milling. Except for the Fe in brown rice, concentration of the nutrients in brown and white rice increased with declining yield. Thus the concentration of nutrients was generally highest in the cool season, when yield was lowest.

4. Discussion

This study has demonstrated how the yield and quality of rice may be influenced by the climatic condition differently among rice varieties, and that variation in quality of the grain may or may not be related to yield. Grain yield was determined primarily by grain filling, as shown by the close relationship between the parameters ($r = 0.91$, $p < 0.001$). The relative high grain filling percentage represents the greater amount of stored carbohydrate reserves translocated from the culm and sheath to the spikelets has been reported to enhance grain yield (Song et al., 1990). Differential effects of season on the varieties were indicated by significant interaction effects of variety and season on the percentage of filled grain and the number of tillers and panicles, although the number of spikelets, thus the size of the sink, was unaffected by season. Rice varieties have been reported to differ in the optimum temperature during grain filling (Yoshida, 1981). However, the present study has shown that yield formation may also be influenced by events that took place earlier. The negative correlation between percentage of filled grain and the number of tillers and panicles suggested that extra cool season tillers and panicles had become a competing sink for photosynthate by grain filling stage. Indeed, large number of unproductive tillers has been identified as a major constraint to increase yield potential in new rice cultivars, and attempts have been made to overcome this in breeding for new plant type by controlling tiller production (Peng et al., 1999).

Analysis of the frequency distribution of the weight of single rice grain enabled the environmental effect on grain filling to be evaluated in detail. The maximum size of the single rice grain is limited by the rigid hull, a fixed characteristic of each variety (Chen et al., 1994; Zeng and Shannon, 2000). The modal grain weight, which represents the typical grain size for each variety, remained constant over the seasons. Variation in the weight of individual grain below the modal value, however, indicated differential season effect on grain filling of different rice varieties. In the cool season the single grain weight at less than 10% of the modal weight accounted for 52% of the grain in CNT1 and 44% in PTT1, compared with only 14% in SPR1 and 26% in RD21. The close

Table 4
Iron and zinc concentration in brown and white rice in four rice varieties grown in three seasons in Chiang Mai, Thailand.

Variety	Season	Iron		Zinc	
		Brown rice	White rice	Brown rice	White rice
		(mg Fe kg^{-1})		(mg Zn kg^{-1})	
SPR1	Wet	8.0d	2.7	21.0a	16.0b
	Cool	8.8e	3.8	28.9b	21.2e
	Hot	10.5i	2.5	23.1a	17.6c
CNT1	Wet	8.0d	3.2	22.2a	18.3c
	Cool	8.7e	4.2	35.1c	30.2g
	Hot	9.1f	3.5	22.3a	16.1b
PTT1	Wet	7.6c	2.5	22.8a	18.2c
	Cool	9.6h	3.8	38.2c	32.6h
	Hot	9.4g	3.6	24.7ab	19.5d
RD21	Wet	6.3a	2.3	20.7a	14.6a
	Cool	7.0b	3.0	26.1ab	24.2f
	Hot	9.7h	3.1	23.0a	16.2bc
Variety mean					
SPR1		9.1	3.0	24.3	18.3
CNT1		8.6	3.6	26.5	21.5
PTT1		8.9	3.3	28.6	23.4
RD21		7.7	2.8	23.3	18.3
Season mean					
	Wet	7.5	2.7a	21.7	16.8
	Cool	8.5	3.7c	32.1	27.1
	Hot	9.7	3.2b	23.3	17.4
Variety		$p < 0.001$	$p < 0.001$	$p < 0.01$	$p < 0.001$
Season		$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Variety × season		$p < 0.05$	NS ($p < 0.05$)	$p < 0.05$	$p < 0.01$
Correlation (r), with significance by analysis of variance					
Between brown and white rice		0.40 $NS_{0.05}$		0.97 $p < 0.001$	
With grain yield		−0.21 $NS_{0.05}$	−0.71 $p < 0.05$	−0.90 $p < 0.01$	−0.90 $p < 0.01$

Significant effects by analysis of variance ($LSD_{0.05}$ in brackets)

correlation between% filled grain and average temperature from transplanting to panicle initiation ($r = 0.91$, $p < 0.001$) suggested the seasonal effects on yield operated primarily through grain filling. The variation in the proportion of filled grain across the varieties in the cool season is possibly related to differential responses of the physiological processes involved in the varieties according to their genetic background. Verifying the reason behind the empty glumes as the failure of grain set or grain filling should lead to identification of the critical yield formation process. Fertilization failure is less likely to be the main reason for empty glumes in the cool season than in the hot season when the maximum temperature during anthesis was much higher. That leaves the varieties' ability to translocate photosynthate into the grain as the possible explanation for the varietal difference in the percentage of grain with modal weight in the cool season.

Percentage head rice and grain chalkiness are critical price determinants in many markets (Efferson, 1985). For example, percentage of head rice (with ≥4/5 full grain length) and allowable number of chalky grain are the criteria specified in the quality standards for Thai rice, including the international benchmark Thai 100%B (Ministry of Commerce, 1997, 2016). The alkaline spreading value is inversely related to gelatinization temperature. The crystalline structure of the starch is dissolved during gelatinization (Fitzgerald et al., 2009), the greater spread of the grain in alkali is indicative of the lower temperature required for dissolution of the crystaline structure. With the highest possible alkaline spreading value of 7, KDML105 that produces the premium grade and priced Thai Hom Mali rice is cooked more rapidly and retains the soft gel like texture when cool. In non-glutinous rice, the firm texture which is prefered in some regions (Calingacion et al., 2014) tends to be associated with higher amylose content. With the alkali spreading value of 2 in the glutinous variety RD4, the standard for high gelatinization temperature, the relationship between amylose content and texture of cooked rice does not appear to be linear.

Percentage head rice, grain chalkiness and alkaline spreading value of the four rice varieties in this study were affected differently by season, but independently of the grain yield. The head rice yield was consistently high across seasons in RD21, but varied with season in the other varieties, with the wet season crop producing the highest head rice yield in SPR1 and CNT1. High air temperature during grain filling stimulates the formation of chalky grain (Tashiro and Wardlaw, 1991; Wakamatsu et al., 2007) and a recent publication additionally indicated that reduced rate of photosynthesis also caused of the chalky grain (Wada et al., 2014). In the present study, all rice varieties produced grain with the highest level of chalkiness in the hot season, when temperature during grain filling rose to 38 °C during the day and 26 °C at night. The season effect on chalkiness, however, varied with the rice varieties. In the hot season SPR1 produced grain with 75% chalkiness, 2.5 times as much as PTT1, although both varieties had similar very low chalkiness in the cool season. Some authors have suggested that chalkiness, which is easy to measure including on individual grains, could be used as a proxy for head rice yield in breeding programmes, based on the close association they found between chalkiness and head rice yield (Zhou et al., 2015). Increasing night temperature associated with global warming may cause of grain chalkiness variation across varieties as it has been reported to cause of reducing grain yield which could be partly explained by the increasing of respiration rate that reduce the level of assimilated available for growth and yield and the potential of this physiological process vary among rice varieties (Yoshida, 1981; Peng et al., 2004). However, while the relationship may have held in that study with a specific set of rice genotypes and nitrogen supply as the environmental variable, the correlation was not significant in the present study. The consistently high head rice yield of RD21 suggested some inherent strength against milling breakage, this and the correlation between head rice yield and alkali spreading value deserve a closer study. The practical implications of the interaction

effects of variety and season on head rice yield, grain chalkiness and alkali spreading value depend on the specific rice varieties. As parboiling effectively strengthens the rice grain against milling breakage and completely eliminates chalkiness (Bhattacharya, 1969), the seasonal effect that lowers head rice yield and increases chalkiness is not a cause for concern with varieties such as SPR1 and CNT1 which are used in producing parboiled rice. The increase in grain breakage and chalkiness, on the other hand, would be detrimental to consumer acceptance and hence the economic value of the rice marketed and consumed as 'white' (i.e. ordinary milled) rice as the price of milled white rice is determined by the percentage of head rice, with 100% head rice receiving the highest price, and price decreasing with increasing percentage of broken rice. Significant decreases in alkali spreading value which increases gelatinization temperature would also be problematic for soft-textured rice like RD21, and especially the aromatic and premium priced PTT1.

In addition to yield and grain physico-chemical quality, nutritional quality of the rice grain was also affected by season. Previous studies reported that rice grain N concentration is influenced largely by external N supply (e.g. Perez et al., 1996; Leesawatwong et al., 2003), while the grain P is much less responsive to external P (Slaton et al., 2002), although large genotypic variation has been reported (Rose et al., 2010). The grain Fe and Zn concentration in the four rice varieties in this study were in the same low level as other mega-varieties of Thai rice but considerably lower than several local varieties previously reported (Saenchai et al., 2012). In the wet season when yield was highest, the variation in the grain N, P, Fe and Zn concentrations among the rice varieties in this study was relatively small. The negative correlation between grain yield and nutrient concentration suggested that the seasonal variation in concentration of the nutrients was likely the result of a simple dilution effect.

In conclusion, rice varieties were shown to respond differently to the climatic environment in their grain quality as well as yield. A simple dilution effect on nutritional quality was indicated by inverse relation between grain yield and the concentration of nitrogen, phosphorus, iron and zinc in the endosperm, i.e. the white rice normally consumed by rice eaters. The physico-chemical property of the rice grain that are determinant of rice grades and prices, including head rice yield, grain chalkiness and gelatinization temperature, on the other hand, varied with variety and season independently of grain yield. These will need to be taken into account in evaluation of rice genotypes for adaptation to climate change.

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